Wood Louisa E (Orcid ID: 0000-0002-8649-5010)

Biosecurity and the ornamental fish trade: a stakeholder perspective in England

Louisa E. Wood[1, 2*a], James Guilder[1*], Marnie L. Brennan[3], Nicola J Birland[3], Virginia Taleti[1], Nicholas Stinton[1], Nick G. H. Taylor[1], Mark A. Thrush[1]

[1]Centre for Environment Fisheries and Aquaculture Science, Weymouth, Dorset, DT4 8UB, UK

[2]Centre for Blue Governance, Faculty of Economics and Law, University of Portsmouth, Portsmouth, P01 3DE, UK

[3]School of Veterinary Medicine and Science, University of Nottingham, Sutton Bonington Campus, Loughborough, LE12 5RD, UK

[a] Corresponding Author

Email address: louisa.wood@cefas.co.uk

Postal address: Centre for Environment Fisheries and Aquaculture Science, Barrack Rd, Weymouth DT4 8UB

Funding information: This work was funded by the School of Veterinary Medicine and Science at the University of Nottingham, with some financial support from the Department for Environment Food and Rural Affairs (Defra) contracts F1172, FB002 and FC1214 awarded to Cefas.

*Louisa E Wood and James Guilder contributed equally to the writing of this manuscript

Abstract

The freshwater and marine ornamental fish industry is a primary pathway for hazard introduction and emergence, including aquatic animal health diseases and non-native species. Prevention measures are key to reducing the risk of hazard incursion and establishment, however, there is currently little understanding of the biosecurity practices and hazard responses implemented at post-border stages of the ornamental fish supply chain. This study addressed this knowledge gap, using questionnaires to collate information on actual biosecurity behaviours and hazard responses practised by ornamental fish retailers and hobbyist communities in England. Actual behaviours varied considerably within retailers and hobbyists, suggesting that reliance on preventative practices by individuals in the post-border stages of the ornamental fish supply chain is likely to be ineffective in minimising the risk of hazard incursion and establishment. Resources should be allocated towards improving and enforcing robust pre-and at-border control measures, such as risk-based surveillance of ornamental fish imports at border controls. In addition, these findings should be used to implement targeted awareness-raising campaigns and help create directed training on biosecurity practices for individuals involved in the post-border stages of the ornamental supply chain.

Keywords: biosecurity practices; exotic pathogens; invasive non-native species; hobbyist; ornamental fish industry; retailer

Introduction

The freshwater and marine ornamental fish trade is a global industry that involves the translocation of over one billion individual fish on an annual basis (Maceda-Veiga et al., 2016). In the UK alone, the Ornamental Aquatic Trade Association (OATA) estimates that the industry is worth £400 million per annum to the retail economy, employing approximately 12,000 people (King, 2019). Stakeholders involved in the industry are diverse (see Figure 1).

Despite the socio-economic benefits of the ornamental fish trade, the industry represents a primary pathway of hazard introduction and emergence, including aquatic animal diseases and non-native species (Chan et al., 2019). Globally, the ornamental fish trade is a known route of exotic pathogen and parasite translocations (Trujillo-González et al., 2018; Whittington and Chong, 2007;), with detrimental ecological (e.g. parasitic nematode *Spirocamallanus istiblenni* Noble, 1966 in Gaither et al., 2013) and economic consequences (e.g. the dwarf gourami iridovirus (DGIV) in Rimmer et al., 2015). Furthermore, intentional release or escape of ornamental fish species from secure systems represents a major vector for non-native fish introductions and translocations globally (see Chan et al., 2019 for a global review). Accidental escape from fish farms, for example from pond drainage or overflow during flood and spate events is possible (Naylor et al., 2001), and deliberate release of unwanted fish has been reported (Copp et al., 2005; Gertzen et al., 2008; Marková et al., 2020). Some cultural and religious groups have also released ornamental fish species as part of rituals, such as mercy, prayer or religious release (Wasserman et al., 2019). In England, the ornamental fish industry has been recognised as a route of introduction for World Organisation for Animal Health (OIE) listed diseases, such as Koi Herpes Virus (KHV) and Spring Viraemia of Carp (SVC). Incursions of both pathogens have been detected in health certified consignments of imported ornamental fish during routine random testing of imported stocks (Taylor et al., 2010, 2013). Historically, several non-native fish introductions to England's waterways have been attributed to the ornamental trade (Copp et al., 2007), such as the release of pet goldfish (*Carassius auratus* Linnaeus, 1758), which have been reported in London ponds since at least the 1950s (Wheeler, 1958). Interestingly, the frequency of occurrence of non-native ornamental varieties has been found to increase with decreasing distance from the nearest road, footpath or inhabitation; emphasising the role of humans in non-native species introductions (Copp et al., 2005). The introduction of ornamental fish species remains a concern, and there have been several incidences of non-native ornamental fish observed in the aquatic environment in England over recent years (Copp et al., 2005; Dowling, 2019; Yule, 2019).

In recognition of the biosecurity[1] risk associated with live ornamental fish transport (Peeler and Taylor, 2011), England's ornamental fish industry is heavily regulated through 'The Aquatic Animal Health (England and Wales) Regulations 2009 (SI 2009/463)', hereafter referred to as the Aquatic Animal Health Regulations (2009), which implements European Council Directive 2006/88/EC[2]. To minimise the risk of notifiable disease introduction through contaminated consignments, imports of ornamental fish into England are subject to national measures that are listed in The Aquatic Animal Health Regulations 2009[3]. Pre-border and at-border prevention measures include controls on trade and movements of live animals, health certification, border inspection protocols, and documentation of stock movements (King, 2019). The relevant prevention measures applied depend on the source of ornamental fish imports. Measures implemented for EU imports have also changed subsequent to EU Exit.

[1] The term 'biosecurity' refers to measures used to prevent introduction of unwanted biological agents, particularly pathogens and non-native species, and to manage adverse effects associated with them.
[2] Applicable at the time of the study, but subject to change from 1st January 2021
[3] Applicable at the time of the study, but subject to change from 1st January 2021

For example, historically, all EU imports into England that are susceptible to, or vectors for, listed diseases, or intended for aquaculture, were subject to risk-based surveillance and had to be accompanied by a health certificate from the Competent Authority in the Member State of origin, stating that the animals had been sourced from zones or compartments declared officially free of relevant diseases and notified on the European 'Trade Control and Expert System' (TRACES)[4]. EU imports could enter through any UK port. Following the UK's exit from the EU on 1st January 2021 all consignments of aquatic animals must continue to be accompanied by a health certificate and are now notified on the Import of Products Animals Food and Feed System (IPAFFS) prior to import. From March 1st, 2022, all consignments from the EU will be restricted to entry through a UK Border Control Post (BCP) that is authorised to handle live fish (Edinburgh, Gatwick, Heathrow and Manchester). All EU imports will therefore be treated the same as those from third countries, which are imported through authorised BCPs.

Due to logistical and resource constraints approximately 10% of consignments that are imported through authorised BCPs are physically inspected by the Animal and Plant Health Agency (APHA) veterinary officers (OV); primarily to ensure species contained within the consignments match the paper records. No disease testing is carried out at the BCPs with the exception of a risk-based surveillance programme for SVC, where all suppliers of SVC susceptible species have a consignment tested for SVC at least once per year. This is implemented by the Centre for Environment Fisheries and Aquaculture Science (Cefas) Fish Health Inspectorate (FHI) which, acting on behalf of Defra, has statutory responsibility for the control of notifiable and emerging disease in aquatic animals in England.

[4]Applicable at the time of the study, but subject to change from 1st January 2021

All businesses importing coldwater ornamental fish require a biosecurity plan and may be subject to site inspection and disease testing by the FHI. Additionally, any person importing ornamental fish must have prior authorisation as a Aquaculture Production Business (APB). Requirements for authorisation vary dependent upon whether the species being imported are susceptible or non-susceptible to listed notifiable diseases, and whether the importer is a business, hobbyist or aquarium. Key legislative measures to prevent the introduction of non-native fish species into England are reviewed in Chan et al. (2019), and include import controls, risk screening and/or risk full assessment, a list of non-native species suitable for import, a list of controlled or prohibited non-native species, and release controls (prohibitions against the release of non-native species into specified environments).

The ornamental fish supply chain is complex and involves a number of different actors (Figure 1). This complexity, coupled with the sheer quantity of trade, means that pre-border and at-border controls are not failsafe and offer limited protection against new and emerging hazards. This is supported by the fact that outbreaks of SVC and KHV in the UK have been directly linked to imported fish (Taylor et al., 2010, 2013). Voluntary implementation of robust biosecurity measures post-border control is vital to prevent the introduction of hazards to the industry and to minimise disease outbreaks and non-native species introduction and spread. Good biosecurity practice is promoted in the industry, whereby stakeholders are encouraged to support and become members of trade associations, such as the Ornamental Aquatic Trade Association (OATA) (King, 2019). Organisation specific codes of conduct or charters are put in place to promote high standards that members must meet and adhere to (Stevens et al., 2017). Any member found to be bringing the industry into disrepute is subject to disciplinary procedures. However, membership itself is voluntary (King, 2019) and OATA estimates that only approximately 50% of the industry in the UK are members. Further, whilst good practice is thought to be the norm rather than the exception, a historic lack of engagement with the industry by key stakeholder groups means there is little understanding of biosecurity practices and trading patterns carried out within these groups (King, 2019).

Retailers of ornamental fish and hobbyists that keep fish in closed facilities (i.e. an indoor aquarium or a garden pond that is no bigger than an acre with minimal risk of fish escape) represent the last stages of the ornamental supply chain and 'the last line of defence' against the introduction and spread of ecological hazards from confinement to the wild. Types of ornamental fish retailers and hobbyists vary considerably, from small pet shops to large retail chains, and from casual fish owners to highly experienced life-time hobbyists. In this paper, we assess the general biosecurity practices and responses to biosecurity hazards practised among different types of retailer and hobbyist in England, to review the potential risk of hazard introduction and transmission along the ornamental supply chain. Several such assessments of biosecurity practices have been carried out elsewhere in the livestock industry (Aleri et al., 2020; Delpont et al., 2018; Damiaans et al., 2019; Gunn et al., 2008), and globally in the ornamental aquatic trade (Patoka et al., 2014; Saengsitthisak et al., 2021), however to our knowledge no such assessment has been completed for stakeholders in the ornamental fish trade in the UK. The study has three objectives: a) to understand the types of key stakeholder groups within the ornamental supply chain, b) to investigate biosecurity practices and hazard responses implemented by each stakeholder group, c) to identify where risk mitigation measures could be implemented to improve biosecurity and provide evidence-based advice to the industry.

Methods

Retailer survey

This telephone questionnaire-based study focused on retail outlets in England. The sampling frame used was the Yell website (www.yell.com) a popular online telephone directory of businesses. To minimise geographical bias related to fish movements, participants were selected by ceremonial county (legally defined by the Lieutenancies Act (1997)). The ceremonial county ‘City of London’ did not yield any results and was therefore not included in the study. Within each county, the results were filtered further using the predefined categories < ‘pet shops’ OR ‘aquarium & pond supplies’ > AND < ‘fish’ >. Using this method, Cornwall and Cumbria did not return any results within the ‘pet shop’ filter’ and thus the term ‘pet fish’ was substituted. A computational random number generator (www.random.org) was used to select which business to contact from the list of results within each of the categories. A target minimum number of three successfully completed questionnaires were sought for each county.

The questionnaire was conducted by telephone survey between October and November 2013. The aim of the survey was explained to each respondent and all were asked if they wanted to be notified of the survey results. A questionnaire comprising 38 questions was developed and refined in collaboration with industry experts to provide a general evaluation of the biosecurity risk presented by the ornamental retail industry (see Supplementary material). Data was collated on biosecurity practices, and knowledge of, and response to, potential hazards, including OIE listed diseases of concern to England’s ornamental industry and general parasitic and disease hazards. To highlight any potential trends across the sector, respondents were asked to identify whether they considered themselves to be a small retail unit, a small retail chain, a large retail unit or a large retail chain, and whether they were a member of OATA. To determine the potential risk of hazard introduction to a retail site, respondents were asked to identify their source(s) of consignments, the type of fish purchased, observed levels of disease or mortality (Death on Arrival), any preventative actions taken by retailers including quarantine measures for any new or returned stock and any prophylactic treatments applied. Respondents were then asked to provide information on the measures taken to minimise the spread of hazards both within their retail site and to the environment from retail facilities, and whether they used individual water filtration systems, sterilised or used separate equipment between tanks or ponds, and/or kept fish in closed topped tanks or ponds. To understand retailer knowledge and response to hazards, respondents were asked about their pre-existing awareness of OIE listed diseases and how they would respond if such a disease or any other pathogen were suspected on site. This included both who they would inform and how they would treat the fish.

Hobbyist survey

This online questionnaire-based study focused on hobbyists in England. The semi-structured questionnaire was implemented using survey software (www.surveymonkey.com), and refined in collaboration with industry experts (see Supplementary material). Respondents had to answer all questions and could only proceed to the next page once all questions had been answered. The survey was promoted on social media via Twitter (Cefas, OATA), Facebook (FHI), and specialist websites (Practical Fishkeeping Magazine (PFKM), Pets at Home). In addition, several fish keeping clubs were contacted to promote the survey such as British Koi Keepers Society (BKKS), and the Derby and District Aquarists Society. Survey cards containing the hyperlink to the questionnaire were distributed through several retail outlets. Only respondents that reported they sourced stock from retailers were included for the purposes of this study.

The questionnaire was conducted between 20th January 2016 and 20th June 2016. It aimed to determine the risk of hazard introduction from retailers to hobbyist communities, and the subsequent risk of hazard introduction to the environment by hobbyists. To highlight any potential trends across hobbyist communities, respondents were asked to identify whether they considered themselves to be a beginner hobbyist, general long-term keeper, informed enthusiast, or expert keeper. To determine the risk of hazard introduction to hobbyist stock, respondents were asked to identify the number of sources of fish stock, observed levels of disease in newly purchased stock, types of disease observed and any preventative actions taken by hobbyists, including the quarantine methods for any new stock. To understand hobbyist responses to hazard detection, respondents were asked how they would respond if they suspected fish were diseased. In addition, to assess the potential introduction of hazards to the environment, respondents were asked what they do with dead, sick and unwanted fish.

Data collation

Completed surveys were entered into an Excel spreadsheet and stored, adhering to Cefas policies on the collation and storage of information. Summary statistics were calculated for survey questions in R v.6.3.1 (R Core Team, 2020).

Ethics statement

The retailer questionnaire and the hobbyist questionnaire received ethical approval from the Ethics Committee at the School of Veterinary Medicine and Science at the University of Nottingham and Cefas respectively. This study adheres to Cefas policies on the collection and storage of information. No personal data was collected in the execution of the questionnaires.

Results

Retailers

General characteristics of retailers surveyed

In total 498 businesses were contacted with 149 agreeing to participate in the study (29.5% response rate), and a total of 147 completing all questions within the questionnaire. Respondents were most commonly from small independent retailers (42%), followed by large independent retailers (31%), and large retail chains (24%). Only a small number of responses were obtained from small retail chains (3%).

Half of all retailers (50%) were registered with the OATA, with a higher proportion of large retail chains reporting membership (91%) than any other retailer type. Over half of all retailers (53%) were aware of the OATA guidelines, which again was highest in large retail chains (89%) and lowest in small retail chains (20%) (Figure 2a, Supplementary Table S1).

Ornamental fish stocked across all retailers were evenly split between cold (median = 40%, quartile 1 = 30%, quartile 3 = 50%) and tropical (median = 50%, quartile 1 = 40%, quartile 3 = 60%) freshwater species. There were relatively few retailers that stocked marine species (median = 0%, quartile 1 = 0%, quartile 3 = 10%), however, one specialist small independent retailer stocked solely marine fish. Across all retailer types, a median of 60 coldwater fish (quartile 1 = 30, quartile 3 = 150) were imported from outside the UK weekly, with one large independent retailer importing up to 5,000 fish per week (Supplementary Table S1).

The primary source of coldwater fish for all retailers was UK wholesalers (see Figure 1). Over two thirds of retailers sourced coldwater stock only from wholesalers (68%), while a further 16% reported sourcing coldwater stock from both wholesalers and directly from overseas (EU and third countries). All but one of the small retail chains purchased stock from wholesalers (80%), whilst only 53% of large independent retailers stocked coldwater fish from wholesalers. Large independent retailers appeared more likely to only source coldwater fish from overseas (24%) compared to the other retailer types (Figure 2b, Supplementary Table S1).

Hazard introduction to retail site

Reported mortality levels in stocked fish, across all retailers, was low with a median of 2% (quartile 1 = 1%, quartile 3 = 3%) of fish, from each batch, estimated to die. There were no clear differences between retailer types. Reported incidence of disease in newly acquired fish across retailers was also low with a median of 2% of batches estimated to be infected (quartile 1 = 1, quartile 3 = 5).

Approximately 56% of retailers quarantined newly acquired fish by separating stock before putting them on sale (Supplementary Table S2). Of retailers that practised some form of quarantine, 46% quarantined new fish for more than a week. In general, quarantine periods appeared to be longest at large independent retailers, with 15% quarantining for over 27 days in this category (Figure 3a, Supplementary Table S3). Two thirds of retailers that quarantined (66%), specifically mentioned isolating the fish by either keeping them off display or on a separate filtration system. This practice was most commonly reported by large independent units (78%) and least commonly reported by large retail chains (38%) (Supplementary Table S3).

All retailers treated water discharged from quarantine tanks but less than half used a UV filtration system (46%). Other filtration systems reported were mechanical filters (78%), biological filters (78%) and carbon filters (6%). The use of UV filtration systems was most frequently reported by large retail chains (77%) (Supplementary Table S3).

Of the 65 respondents that did not quarantine, two thirds mentioned that they thought quarantine took place prior to acquisition (e.g., at the wholesalers) (Figure 3b). However, 17% of all retailers neither reported carrying out quarantine of fish on site nor suggested this took place prior to purchase. One of the respondents relied on health certificates from the country of origin (Supplementary Table S2).

Two thirds of all retailers allowed customers to return fish shortly after purchase (66%), with over half of these re-introducing the returned fish to the rest of the stock without any quarantine (52%) (Figure 3c). Large and small retail chains appeared most likely to re-introduce returned fish without quarantine (53% and 60% respectively), while large independent retailers appeared most likely to either quarantine any fish that are returned (47%) or not accept any returns (33%) (Supplementary Table S2).

Most retailers would also prophylactically treat new batches of fish (73%), predominantly with antibacterials (33%), antifungals (23%) and/or antiparasitics (25%) (Supplementary Table S2).

Hazard transmission within retail site

Over half of all retailers used separate dip nets between tanks, with this proportion apparently highest in large retail chains (60%). Less than a quarter of retailers treated the nets with antibacterial dips between different tanks or ponds (22%); this was least frequently reported by large retail chains (11%) (Supplementary Table S2).

Less than half of retailers had open topped tanks or ponds on site (42%) providing the opportunity for local fomite spread (e.g., birds), both within the site or to the wider environment. Open top containers appeared to be most common in large independent retailers (62%) and small retail chains (60%) (Supplementary Table S2).

Response to hazards by retailers

Nearly two thirds of all retailers reported no prior knowledge of OIE listed diseases (65%), which included 83% of large retail chains and 80% of small retail chains. Of those aware of listed diseases, 74% mentioned KHV, 26% Spring Viraemia of Carp, and 11% Epizootic Ulcerative Syndrome. There were also two respondents that considered their carp to come from KHV vaccinated sources even though no effective commercial vaccine was available at the time of the questionnaire. Awareness of listed diseases appeared to be most common in large (47%) and small independent retailers (33%) (Figure 4a, Supplementary Table S4).

Of the 47 retailers that were aware of listed diseases, most suggested that they would quarantine fish suspected to be infected with a listed disease and then inform the relevant authority (64%) (Figure 4b). Of the remaining respondents, reporting routes mentioned were split between Defra, Cefas, OATA, suppliers and vets. Only 3% of retailers that were aware of listed diseases would cull fish if such a disease were suspected (Supplementary Table S4).

Less than one third of all retailers had a named vet (31%) to treat any general health issues. In response to an infected batch of fish, 61% of retailers would inform the suppliers, a practice most commonly reported by large retail chains (86%). If fish were considered to have a health issue, 83% of retailers suggested they would treat the sick fish themselves, and two thirds would both isolate and quarantine the affected and/or exposed fish. The combined treatment and quarantine approach were most commonly reported by large (80%) and small (61%) independent retailers. If retailers were to treat infected fish, 42% would consider a single tank or pond to be one epidemiological unit whereas 16% would consider any tank or pond on the same water system to be one epidemiological unit. 14% of all retailers suggested they would only treat the fish that displayed a health issue. The practice of treating individual tanks or ponds appears to be most common in large (49%) and small (47%) independent retailers, while large retail chains appear most likely to treat the whole system (26%) (Supplementary Table S5).

Hobbyists

General characteristics of hobbyists surveyed

In total 572 responses were received in the study, with a total of 545 complete responses (95%). Of these, 80% sourced their stock from retailers, 8% from other hobbyists and 4% purchased fish through the internet. The remaining hobbyists sourced fish from specialist dealers, wholesalers, fish farms, fish shows, imported directly from overseas or bred their own fish. Two respondents reported collecting fish directly from the wild. Hobbyists that bought fish from retailers, mostly described themselves as informed enthusiasts (43%) and general long-term keepers (36%), with 15% describing themselves as beginners and 6% as experts (Supplementary Table S7).

Hazard introduction to hobbyist site

Hobbyists that sourced fish from retailers most commonly purchased stock from two to five different sources (69%) and purchased fish two to five times per year (56%). A higher proportion of expert keepers sourced fish from more than five different sources (8%) than other types of hobbyist, and also tended to purchase fish stock more often (18%) (Supplementary Table S7).

The most frequently owned type of fish were tropical freshwater fish (38% owned > 11 tropical freshwater fish) and least frequently owned type were marine fish (93% owned no marine fish). Most respondents kept between 11 and 100 fish (68%), with expert keepers tending to keep more fish than other types of hobbyist (only 8% kept less than ten fish). Most hobbyists kept two to five different species of fish (37%), with expert keepers apparently more likely to keep a higher diversity of species than other hobbyist types (Supplementary Table S7).

Among respondents that sourced stock from retailers, just over half (55%) did not quarantine new stock. Quarantine appeared to be carried out more often by expert keepers (67%) and least often by beginner hobbyists (41%). Twenty nine percent of hobbyists said they never observe infection in their tanks or ponds; this was apparently highest in beginner hobbyists (34%) and lowest in specialist or expert keepers (19%). The most common causes of infection in descending order were parasites (34%), fungal infections (13%) and bacterial infections (12%).

Response to hazards by hobbyists

Only 15% of all hobbyists would visit the vet in the event of sickness, with little differences observed between hobbyist types. The most common source of advice for hobbyists in the event of disease occurrence was the internet (52%). Expert keepers appear least likely to seek advice (48%) and in direct contrast, beginners appear most likely to seek advice (75%).

Less than half of all respondents would treat fish in the event of sickness (44%); treatment appears to be more commonly practised among expert keepers (74%) than beginner hobbyists (45%). Of hobbyists that treated sick fish, most believed treatment to be effective, with 62% of respondents reporting that approximately 1 in 3 treatments were successful. Expert keepers perceived treatment to be effective more often than other retailer types with 81% reporting that 1 in 3 treatments were effective (Supplementary Table S7).

Hazard transmission to the environment

Most hobbyists reported disposing of dead fish at home safely (in compost, bin etc.) (77%), with 16% reporting that they would dispose of dead fish in the toilet. Only one respondent (informed enthusiast group) reported that they disposed of dead fish in a local pond or river. Safe disposal practices appeared to be more common in informed enthusiasts than other hobbyist groups. Beginner hobbyists (17%) and general long-term keepers (20%) were apparently most likely to dispose of dead fish in the toilet (Figure 5a, Supplementary Table S7).

Almost half of all respondents did not provide a clear answer as to what they would do with sick fish (43%) and nearly half indicated that they would treat the sick fish or dispose of it in a safe manner (compost, bin, incineration etc) (49%), this practice was potentially highest in the expert keeper group (63%). Only 2% of all hobbyists would return fish to the dealer, and 5% would dispose of sick fish in the toilet (Figure 5b, Supplementary Table S7).

Over one third of respondents did not indicate what they would do with an unwanted fish (many indicating they had not had unwanted fish) (38%), with 4% euthanising the fish and then safely disposing of it, and 56% trading the fish (either returning to dealer or selling/giving to another hobbyist). Two beginners, two informed enthusiasts and one expert keeper reported releasing unwanted fish into a local pond or river (1%) (Figure 5c, Supplementary Table S7).

Discussion

The ornamental fish trade is a key pathway of hazard introduction and emergence, including aquatic animal health diseases and non-native species. Given that pre-border and at-border prevention measures are not failsafe, implementation of effective biosecurity and hazard response behaviours are required at post-border stages of the supply chain to mitigate risks.

However, understanding of key stakeholder behaviours surrounding the implementation of biosecurity measures and hazard responses remains limited. This study addresses this knowledge gap, using semi-structured questionnaires to collate information on actual biosecurity behaviours and hazard responses within ornamental fish retailers and hobbyist communities in England. To our knowledge, this study is the first to analyse actual practices within key stakeholder groups in the ornamental fish industry in the UK.

Stakeholder behaviours are thought to be influenced by individual attributes, including demographic characteristics, experience of the hazard, knowledge systems, social relations and value systems (Shackleton et al., 2019). This study furthers our understanding of the individual attributes of two key stakeholder groups in the ornamental fish supply chain. Results of this study illustrate that a diverse array of stakeholders operate within the English ornamental fish supply chain, with retailers self-identifying based on size and business model, and hobbyists self-identifying based on experience. This survey returned similar results to OATA estimates in King et al. (2019); approximately half of all retailers in this study reported to be members of OATA, with membership highest in large retail chains. Variation also exists in stakeholder awareness of biosecurity hazards between retailer types, with knowledge of OIE listed diseases seemingly highest in large independent retailers. However, only 32% of retailers in this survey reported prior knowledge of OIE listed diseases, with KHV being the most well-known OIE listed pathogen. KHV has been a problem within the UK cyprinid industry (which includes both ornamental and coarse fish) (FHI, 2017, 2018, 2019) for several years and has recently been detected in wholesaler/retailer premises, resulting in the mandatory culling of stock and disinfection of the premises[4].

[4]https://www.gov.uk/guidance/prevent-fish-or-shellfish-diseases#control-areas-for-notifiable-disease-outbreaks

It therefore follows that retailers that stock KHV susceptible species in this study (particularly Koi carp) are more aware of this disease in comparison to other listed diseases. Temporal comparison of stakeholder awareness of OIE listed pathogens would provide valuable insight into how stakeholder experience affects their awareness of different hazards.

Biosecurity practices and response to hazards

Actual biosecurity measures and hazard responses implemented by retailers and hobbyists vary considerably in this study. Quarantine measures, whereby new stock is isolated for a 'suitable period' and 'no transfer of fish, water, waste products, gametes or equipment is permitted'[5], is a recommended biosecurity measure to minimise the risk of disease introduction to a site. This study indicates that only half of all ornamental retailers practice some sort of quarantine of new stock (57% of these were registered with OATA), with very little consistency in the duration and conditions in which quarantine is practised. Similarly, just less than half of all hobbyists quarantined new stock, a practice more common in experienced hobbyists.

Furthermore, this study suggests that stakeholder perceptions of quarantine practices carried out further up the supply chain may influence whether quarantine is implemented by the retailers themselves. Almost two thirds of retailers who did not quarantine indicated that they believed their stock had been pre-quarantined, most often at wholesalers, and therefore considered quarantine of new arrivals to be unnecessary. One retailer reported receiving stock directly from China, however as the fish were accompanied by a health certificate, they did not quarantine on site. Reliance on other stakeholder groups to implement good biosecurity practices is a potentially unacknowledged risk factor in hazard transmission in the ornamental trade and should be addressed.

[5] https://ornamentalfish.org/wp-content/uploads/2012/08/Biosecurity.pdf

In addition to a period of isolation, OATA guidelines highlight that effective biosecurity requires a period of preventative acclimatisation when species traded are known hosts of high-impact diseases, such as OIE listed pathogens. Preventative acclimatisation requires keeping of fish in conditions in which the pathogen of concern would normally cause clinical disease or otherwise become detectable. This is particularly important if the pathogen can remain latent in fish for significant periods of time and may not be detected at BCPs, as is the case for KHV (Xu et al., 2013; Zheng et al., 2017). In this study, a minority of retailers (10%) and hobbyists (11%) that stocked KHV susceptible cyprinid species, voluntarily reported carrying out a period of preventative acclimatization that would be suitable for the detection of KHV in fish stock. This involved the gradual increase of water temperatures, from 18-24°C, over a period of up to 30 days.

Biosecurity measures to prevent hazard introduction onto a site should be combined with measures to prevent spread, for example via the water supply or translocation on fomites[6]. In this regard, the use of individual filtration systems and disinfection or separation of equipment such as nets, is regarded as good practice[6]. In this study, most retailers either treated or used separate nets between tanks suggesting awareness of the importance of sterile equipment, however less than a quarter of all retailers reported using individual filtration systems. The direct transfer of pathogens on fomites is a risk factor for the spread of OIE listed fish diseases including infectious haematopoietic necrosis (IHN), infectious salmon anaemia (ISA) and KHV (Hattenberger-Baudouy et al., 1988; Jarp and Karlsen, 1997). However, mechanical transmission routes have been little explored within the UK ornamental fish industry, and currently no data exists to assess the level of connectivity within retail units across England and the associated implications on disease spread.

[6] https://ornamentalfish.org/wp-content/uploads/2012/08/Biosecurity.pdf

It is evident from this study that release of ornamental fish into the wild if stock is unwanted, sick or dead, is a feasible route of hazard introduction into the aquatic environment. Although only a small percentage of hobbyists reported the discard of fish into the wild in this study, when scaled to represent hobbyist communities at a national level, this pathway may pose a substantial risk for hazard introduction and spread. Release of ornamental species has been implicated as a route of introduction of OIE listed diseases into the UK aquatic environment (Taylor, 2010, 2013). There were nine reported cases of KHV disease across sites in England in 2020 (FHI, 2020). Although not directly attributed to the discard of ornamental imports, molecular evidence points to each mortality episode being a discrete event with no connectivity between them, suggesting that virus seeding occurs via multiple introductions (pers. Comm. David Stone, Cefas). Given that KHV is known is occur in ornamental consignments (Taylor et al., 2010) and hobbyists are known to release hosts of KHV, such as *C. auratus*, into the aquatic environment, a proportion of KHV outbreaks can likely be attributed to the ornamental trade. SVC and epizootic ulcerative syndrome (EUS) are not currently an issue in the UK cyprinid sector, or the UK ornamental industry in general. SVC was prevalent in the UK between 1977 and 2010 and during this period there were 108 confirmed cases (including 22 cases in ornamental wholesalers and retailers). The sporadic nature of the cases and the seasonal variation in temperatures, suggest SVC is unable to persist throughout the year in the UK environment, and a widescale surveillance and eradication programme began in 2005, enabling the UK to be declared disease free in 2010 (Taylor, 2013). There was a solitary SVC case in a fishery in 2017 (FHI, 2017). EUS is considered a primarily tropical and sub-tropical disease (generally requiring temperatures of > 20˚C for clinical expression) which has caused widespread economic and environmental losses in fresh and brackish water throughout Asia, Africa and North America (Herbert et al., 2019). It has a prolific host range; officially 94 species can be naturally infected (OIE, 2019), however, further evidence suggests that *ca* 190 species in 90 genera may actually be susceptible (EFSA, 2008) including coarse species present in the UK: Crucian carp (*Carassius carassius* Linnaeus, 1758), Rudd (*Scardinius erythrophthalmuss* Linnaeus, 1758) and also Rainbow trout (*Oncorhynchus mykiss* Walbaum, 1792) (Kahn et al., 1998; Lilley et al., 1998) which are farmed extensively. Whilst still an OIE listed disease, EUS was removed from the exotic disease list in European Union legislation under Council Directive 2006/88/EC. The above factors may provide some background as to why awareness of SVC and EUS is lower than that of KHV. However, given that all SVC cases between 1977 and 2010 were thought to originate from imported fish, that EUS was detected in a consignment of snakehead species (*Channa aurantimaculata* Musikasinthorn, 2000 and *Channa* spp.) that required the culling of the animal and disinfection of the animals (FHI, 2018), and the estimated financial impact of SVC on individual retailers or wholesalers (circa £20 - 30k) (McGregor, 1997), it is important that there is improved awareness of listed diseases to better protect both the ornamental industry itself and the wider environment.

On the other hand, release of non-native stock into the aquatic environment is unlikely to represent an invasive risk if environmental conditions are not suitable for establishment. In England, existing legislation, such as the Import of Live Fish (England and Wales) Act 1980 (ILFA), restricts the keeping or introduction of non-native freshwater fish species to a defined 'ornamental fish list'. This list mostly comprises tropical, subtropical and some warm temperate fish species, therefore risk of establishment of these species in UK waters is likely to be low at present. However, several species introduced to the UK for commercial purposes that were believed to present minimal risk of establishment, such as the Pacific oyster (*Crassostrea gigas* Thunberg 1973), have subsequently successfully established and caused significant ecological, economic and social impact (Herbert et al., 2012). Furthermore, it is important to consider that disease transmission can occur in the absence of the successful establishment of a new host population, and infected fish may transmit disease to other susceptible host species present in the aquatic environment.

Limitations

It is important to consider limitations in the approach to this study, which may affect conclusions drawn on biosecurity behaviours and hazard responses. Given the absence of a national database of retailers in the UK, and that the actual number of hobbyists is unknown, rigorous random sampling was not possible. However, through encompassing multiple stakeholder types through random sampling, the retailer and hobbyist samples obtained likely captured the heterogeneity of the UK ornamental chain. Nevertheless, small retail chains were underrepresented in this study, which prevented robust comparison of differences in behaviours and responses between retailer types. Further, given the use of telephone questionnaire to target retailers, online trading platforms were likely underrepresented. Results can therefore not be used to determine biosecurity behaviours practiced by online sellers, nor indeed the proportion of ornamental fish traded through this route, and this should be addressed in further work. In addition, by asking hobbyist communities to self-select their level of knowledge and experience based on pre-defined categories, background information such as duration of fish keeping, was lost.

As with all studies of this type, potential discrepancies between stakeholder responses and actual practices render assessments of biosecurity and hazard response behaviours difficult. Respondents may be led by a desire to report what is perceived to be the 'correct response' based on preconceived ideas and knowledge on biosecurity. For retailers, membership of OATA requires compliance with set criteria and adherence to these codes of conduct and charters, which may have affected responses given. Those responding to the questionnaire are likely to be more concerned about biosecurity and likely to follow good practice compared to non-respondents. However, this potential bias could not be evaluated. Future studies should address this limitation by combining the administration of the questionnaire with direct observations of actual practices, although it is acknowledged that access to ornamental retailers and hobbyist communities is likely to be challenging. Follow up work could also consider how technological advancements and legislative changes that have been implemented subsequent to the execution of this study have affected biosecurity and hazard response behaviours in the industry. For example, future studies may consider the impact of the Animal Welfare (Licensing of Activities Involving Animals) (England) Regulations 2018 (SI 2018/486), on the behaviours of ornamental fish retailers, such as the requirement for a named vet as a condition of licensing.

Recommendations

Given identified gaps in biosecurity at the end of the ornamental fish supply chain, preventative measures should focus on pre-border and at-border controls, where efforts to mitigate the risk of hazard incursion are likely to be most effective. Currently, monitoring of ornamental fish imports at BCPs is randomised, with only approximately 10% of ornamental fish consignments visually inspected to ensure fish match the relevant paperwork and to rule out any obvious presence of disease. However, when inaccurate paperwork or disease occurrence is rare, this method of sampling is limited in terms of financial and operational feasibility, requiring a large sample size when prevalence is low (Salman, 2003). Risk-based surveillance of ornamental fish imports presents a more cost-effective approach to the prevention of hazard incursion via this pathway (Stärk et al., 2006). In this instance, sampling of ornamental fish imports would be non-random, taking into account the probability of a hazard occurring in an individual consignment (Oidtmann et al., 2013). Import risk analyses informs risk-based surveillance by providing a comprehensive understanding of risk factors associated with hazard occurrence, such as spatial factors (e.g., trading partners), host factors (e.g., species, age, susceptibility), management factors (e.g., biosecurity, antimicrobial usage) and other factors (e.g., history of cases or risky practices, volume of trade).

Impeding the implementation of robust risk-based surveillance is the lack of available data on the association between hazard occurrence and individual risk factors. For example, an understanding of the ornamental species traded is necessary to assess invasion risk, establishment probability and susceptibility to disease. However, in the UK, it is currently challenging to obtain species level information on the types of ornamental fish being traded as there is little legal obligation to do so (but see Pinnegar and Murray, 2019). Although suppliers must submit a species list within the AHH2 form as a requirement to become an authorised importer of live fish and shellfish in England (Cefas, 2019), once this form is submitted there is little oversight of species present in individual consignments and quantities (Pinnegar and Murray, 2019). Currently, ornamental fish are exported–imported via one of two available harmonised commodity codes; 030111000 for live ornamental freshwater fish and 030119000 for live ornamental fish (excluding freshwater), i.e., marine ornamental fish (Gov UK, 2018). Establishment of a robust electronic system for logging and tracking the import of ornamental fish consignments through BCPs is a first step in assembling a database of traded species to inform import risk analysis. Efforts in this regard have already been initiated in the USA with the development of the Marine Aquarium Biodiversity and Trade Flow online database (https://www.aquariumtradedata.org/); a public portal with anonymised live marine animal trade data collected through trade invoices (Rhyne et al., 2017). Artificial intelligence models may be trained using collected data to inform BCP officials of which consignments may present a higher risk. Machine and deep learning methods can be applied to increasingly complex data to identify trends, patterns and anomalies, and therefore identify potential risk factors (such as the risk factors mentioned above). Such AI techniques are used regularly in public health surveillance, for example to highlight the geographical risk distribution of ZIKV and dengue fever (Akhtar et al., 2019; Ding et al., 2017; Zeng et al., 2020). Ultimately, AI models could then inform human decision making in terms of which consignments require further inspection.

Robust hazard detection and identification protocols are required for effective risk-based surveillance. Currently, visual detection methods are used at BCPs to detect disease occurrence in live ornamental fish imports. However, this approach is limited in circumstances when the infections are subclinical or persistent (St-Hilaire et al., 2005). Further, the presence of non-native species in ornamental imports is not considered in visual testing at BCPs at present. Molecular methods offer new opportunities to improve the detection of hazards in ornamental fish shipments. Environmental DNA (eDNA) has recently emerged as a popular method for detection of DNA that is continuously shed by living organisms into the local environment. Species specific detection methods using quantitative polymerase chain reaction (qPCR; see reviews by Barnes and Turner, 2016; Goldberg et al., 2016; Thomsen and Willerslev, 2015), can be used to screen eDNA to determine the presence or absence of target species. qPCR methods have been shown to be highly sensitive in the detection of parasites in wild aquatic ecosystems and aquaculture (Gomes et al., 2017) and to detect non-native species in invaded systems (Snyder et al., 2020). Once appropriately validated for statutory use, eDNA based methods could be used in a risk-based surveillance programme, as a possible non-destructive, sensitive species-level detection method to target non-native fish species present at low densities within mixed imports of ornamental fish (e.g., Collins et al., 2013), and to detect DNA of pathogens shed by infected fish in the shipment water of imported live ornamental fish.

Improving biosecurity behaviours of stakeholders at post-border stages of the ornamental supply chain requires a combination of interventions, such as education, training, policy instruments and incentives. OATA has provided opportunities to educate industry stakeholders (https://ornamentalfish.org/training/invasive-non-native-species-trainingmodule/), as well as promoting the no-release message and guidelines for effective biosecurity (King, 2019). However, there remains a low, but steady rate of introduction of non-native ornamental fish species into the wild (King, 2019), which is further evidenced by this paper. Efforts to address this issue require an improved understanding of stakeholder's knowledge, attitudes and motivations that are driving the release of unwanted ornamental fishes, which is prohibited under the Wildlife and Countryside Act 1981 (Gov UK, 1981), in order support the implementation of more effective biosecurity campaigns (Polonksly et al., 2004; Prinbeck et al., 2011). Enhanced collaboration between industry stakeholders and UK government bodies, such as the FHI, and the GB Non-Native Species Secretariat (www.nonnativespecies.org), will facilitate a more effective, joined up approach to biosecurity in the ornamental fish industry.

Conclusions

This study highlights that reliance on ornamental fish retailers and hobbyists to minimise hazard transmission and introduction to the aquatic environment is likely to be ineffective. Although retailers are encouraged to implement robust biosecurity practices and hazard response measures through OATA membership, it is evident that practices vary considerably. Behaviours observed in hobbyist communities are equally diverse, and key biosecurity messages, such as bans on the release of stock, appear to have been lost. Until better preventive practices are undertaken by these stakeholder groups, it may be more efficient to target future resources towards improving and enforcing robust pre-and at-border control measures, such as risk-based surveillance of ornamental imports.

Acknowledgements

This work was funded by the School of Veterinary Medicine and Science at the University of Nottingham, with some financial support from the Department for Environment Food and Rural Affairs (Defra) contracts F1172, FB002 and FC1214 awarded to Cefas.

Authors' contributions: NT, MT and NS conceived the ideas and scope of the manuscript; LEW, JG and MT led the writing of the manuscript. NT and MT secured funding for the work. MLB and NC were involved in the process of designing and executing the telephone questionnaire. VT conducted the hobbyist survey. All authors contributed to drafts and gave final approval for publication**.**

Conflicts of interest/Competing interests: The authors declare no competing financial interests.

Significance statement: This study improves our understanding of the biosecurity practices and hazard responses implemented at post-border stages of the ornamental fish supply chain. Behaviours were shown to vary considerably within ornamental fish retailers and hobbyists and it was concluded that reliance on these groups to minimise hazard transmission and introduction to the aquatic environment is likely to be ineffective at present. Resources should be allocated towards improving and enforcing robust pre-and at-border control measures.

References

Akhtar, M., Kraemer, M.U. & Gardner, L.M. (2019) A dynamic neural network model for predicting risk of Zika in real-time. BMC Medicine, 17, 171

Aleri, J. W. & Laurence M. (2020) A description of biosecurity practices among selected dairy farmers across Australia. *Animal Production Science*, **60**, 1711-1720

Barnes, M.A. & Turner, C.R. (2016). The ecology of environmental DNA and implications for conservation genetics. *Conservation Genetics*, **17**, 1-17

CEFAS. (2019). Authorise an importer. Weymouth, England: CEFAS Fish Health Inspectorate. Available at: www.assets.publishing.service. gov.uk/government/uploads/system/uploads/attachment_data/file/53 0276/aah2.pdf

Chan, F.T., Beatty, S.J., Gilles Jr, A.S., Hill, J.E., Kozic, S., Luo, D., Morgan, D.L., Pavia Jr, R.T., Therriault, T.W., Verreycken, H. & Vilizzi, L. (2019). Leaving the fishbowl: the ornamental trade as a global vector for freshwater fish invasions. *Aquatic Ecosystem Health & Management*, **22**, 417-439

Collins, R.A., Armstrong, K.F., Holyoake, A.J. & Keeling, S. (2013). Something in the water: biosecurity monitoring of ornamental fish imports using environmental DNA. *Biological Invasions*, **15**, 1209-1215

Copp, G.H., Wesley, K.J., & Vilizzi, L. (2005). Pathways of ornamental and aquarium fish introductions into urban ponds of Epping Forest (London, England): the human vector. *Journal of Applied Ichthyology*, **21**, 263–274

Copp, G.H., Stakėnas, S. & Davison, P.I. (2006). The incidence of non-native fishes in water courses: example of the United Kingdom. *Aquatic Invasions*, **1**, 72-75

Copp, G.H., Templeton, M. & Gozlan, R.E. (2007). Propagule pressure and the invasion risks of non-native freshwater fishes: a case study in England. *Journal of Fish Biology*, **71**, 148–159

Damiaans, B., Renault, V., Sarrazin, S., Berge, A.C., Pardon, B., Ribbens, S., Saegerman, C. & Dewulf, J. (2019). Biosecurity practices in Belgian veal calf farming: Level of implementation, attitudes, strengths, weaknesses and constraints. *Preventive veterinary medicine*, **172**, 104768

Delpont, M., Blondel, V., Robertet, L., Duret, H., Guerin, J.L., Vaillancourt, J.P. & Paul, M.C. 2018). Biosecurity practices on foie gras duck farms, Southwest France. *Preventive veterinary medicine*, **158**, 78-88

Ding F.Y., Fu J.Y., Jiang D., Hao M.M. & Lin G. (2018). Mapping the spatial distribution of *Aedes aegypti* and *Aedes albopictus*. *Acta Tropica*, **178**, 155–162.

Dowling, T. (2019). Carping on: how did a small pond become home to 10,000 goldfish? The Guardian. Available at: https://www.theguardian.com/environment/shortcuts/2019/may/28/carping-on-how-did-a-small-pond-become-home-to-10000-goldfish

EFSA, 2007. Scientific Opinion of the Panel on Animal Health and Welfare on a request from the European Commission on possible vector species and live stages of susceptible species not transmitting disease as regards certain fish diseases. EFSA J. 584, 1–163.

FHI (2017) FHI Quarterly Report - 1 April to 30 June 2017. Available at: https://www.gov.uk/government/publications/fish-health-inspectorate-reports-2017/fhi-quarterly-report-1-april-to-30-june-2017

FHI (2018) Fish Health Inspectorate Annual Report for 2018. Available at: https://www.gov.uk/government/publications/fish-health-inspectorate-reports-2018/fish-health-inspectorate-annual-report-for-2018

FHI (2019) FHI Quarterly Report - 1 July to 30 September 2019. Available at: https://www.gov.uk/government/publications/fish-health-inspectorate-reports-2019/fhi-quarterly-report-1-july-to-30-september-2019

FHI (2020) Outbreaks of Koi herpesvirus (KHV) disease in 2020. Available at: https://www.gov.uk/government/news/outbreaks-of-koi-herpesvirus-khv-disease-in-2020

Gunn, G.J., Heffernan, C., Hall, M., McLeod, A. & Hovi, M. (2008). Measuring and comparing constraints to improved biosecurity amongst GB farmers, veterinarians and the auxiliary industries. Preventive Veterinary Medicine *Preventive Veterinary Medicine*, **84**(3-4), 310-23.

Gaither, M.R., Aeby, G., Vignon, M., Meguro, Y.I., Rigby, M., Runyon, C., Toonen, R.J., Wood, C.L. & Bowen, B.W. (2013). An invasive fish and the time-lagged spread of its parasite across the Hawaiian archipelago. *PloS one*, **8**, e56940

Gertzen, E.L., Familiar, O. & Leung, B. (2008). Quantifying invasion pathways: fish introductions from the aquarium trade. *Canadian Journal of Fisheries and Aquatic Sciences*, **65**, 1265–1273

Goldberg, C.S., Turner, C.R., Deiner, K., Klymus, K.E., Thomsen, P.F., Murphy, M.A., Spear, S.F., McKee, A., Oyler-McCance, S.J., Cornman , R.S. & Laramie, M.B. (2016). Critical considerations for the application of environmental DNA methods to detect aquatic species. *Methods in ecology and evolution*, **7**, 1299-1307

Gomes, G.B., Hutson, K.S., Domingos, J.A., Chung, C., Hayward, S., Miller, T.L. & Jerry, D.R. (2017). Use of environmental DNA (eDNA) and water quality data to predict protozoan parasites outbreaks in fish farms. *Aquaculture*, **479**, 467-473

Gov UK. (2018). Trade Tariff: look up commodity codes, duty and VAT rates. Retrieved from: https://www.trade-tariff.service.gov.uk/headings/0301

Herbert, R.J.H., Roberts, C., Humphreys, J. & Fletcher, S. (2012). The Pacific oyster (*Crassostrea gigas*) in the UK: economic, legal and environmental issues associated with its cultivation, wild establishment and exploitation. Report for the Shellfish Association of Great Britain

Herbert, B., Jones, J.B., Mohan, C.V. & Perera, R.P. (2019). Impacts of epizootic ulcerative syndrome on subsistence fisheries and wildlife. *Revue Scientifique et Technique*, **38** (2), 459-475

Khan, M.H., Marshall, L., Thompson, K.D., Campbell, R.E. & Lilley, J.H. (1998). Susceptibility of five fish species (Nile tilapia, rosy barb, rainbow trout, stickleback and roach) to intramuscular injection with the Oomycete fish pathogen, *Aphanomyces invadans*. *Bulletin of the European Association of Fish Pathologists*, **18**(6), 192-197

King, T.A. (2019). Wild caught ornamental fish: A perspective from the UK ornamental aquatic industry on the sustainability of aquatic organisms and livelihoods. *Journal of Fish Biology*, **94**, 925-936

Lilley J.H., Callinan R.B., Chinabut S., Kanchanakhan S., Macrae I.H. & Phillips M.J. (1998). Epizootic ulcerative syndrome (EUS) technical handbook. Aquatic Animal Health Research Institute., Bangkok, Thailand, 88 pp.

Maceda-Veiga, A., Domínguez-Domínguez, O., Escribano-Alacid, J. & Lyons, J. (2016) The aquarium hobby: can sinners become saints in freshwater fish conservation? *Fish and Fisheries*, **17**, 860-874

Marková, J., Jerikho, R., Wardiatno, Y., Kamal, M. M., Magalhães, A. L. B., Bohatá, L., Kalous. & Patoka, J. (2020). Conservation paradox of giant arapaima *Arapaima gigas* (Schinz, 1822) (Pisces: Arapaimidae): endangered in its native range in Brazil and invasive in Indonesia. *Knowledge & Management of Aquatic Ecosystems*, **421**, 47.

McGregor, D. (1997). The impact and control of spring viraemia of carp in England and Wales 1988–1997. In: Proceedings 8th European Association of Fish Pathologists, Edinburgh

Naylor, R.L., Williams, S.L. & Strong, D.R. (2001). Aquaculture—a gateway for exotic species. *Science*, **294**, 1655–1656

Oidtmann, B., Peeler, E., Lyngstad, T., Brun, E., Jensen, B.B. & Stärk, K.D. (2013). Risk-based methods for fish and terrestrial animal disease surveillance. *Preventive veterinary medicine*, **112**, 13-26

OIE. (2019). Manual of diagnostic tests for aquatic animals. Chapter 2.3.2. Infection with *Aphanomyces invadans* (epizootic ulcerative syndrome). Paris, France. 14pp.

Patoka, J., Petrtýl, M., & Kalous, L. (2014). Garden ponds as potential introduction pathway of ornamental crayfish. *Knowledge and Management of Aquatic Ecosystems*, **414**, 13.

Peeler, E.J. & Taylor, N.G. (2011). The application of epidemiology in aquatic animal health-opportunities and challenges. *Veterinary Research*, **42**, 94

Pinnegar, J.K. & Murray, J.M. (2019). Understanding the United Kingdom marine aquarium trade–a mystery shopper study of species on sale. *Journal of Fish Biology*, **94**, 917-924

Polonsky, M.J., Binney, W. & Hall, J. (2004). Developing better public policy to motivate responsible environmental behavior–an examination of managers' attitudes and perceptions towards controlling introduced species. *Journal of nonprofit & public sector marketing*, **12**, 93-107

Prinbeck, G., Lach, D. & Chan, S. (2011). Exploring stakeholders' attitudes and beliefs regarding behaviors that prevent the spread of invasive species. *Environmental Education Research*, **17**, 341-352

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available at: https://www.R-project.org/

Rimmer, A.E., Becker, J.A., Tweedie, A., Lintermans, M., Landos, M., Stephens, F. & Whittington, R.J. (2015). Detection of dwarf gourami iridovirus (Infectious spleen and kidney necrosis virus) in populations of ornamental fish prior to and after importation into Australia, with the first evidence of infection in domestically farmed Platy (*Xiphophorus maculatus*). *Preventive Veterinary Medicine*, **122**, 181-194

Rhyne, A.L., Tlusty, M.F., Szczebak, J.T. & Holmberg, R.J. (2017). Expanding our understanding of the trade in marine aquarium animals. *PeerJ*, **5,** p.e2949

Saengsitthisak, B., Punyapornwithaya, V., Chaisri, W., Mektrirat, R., Bernard, J.K. & Pikulkaew, S. (2021). The current state of biosecurity and welfare of ornamental fish population in pet fish stores in Chiang Mai Province, Thailand. *Veterinary Integrative Sciences*, **19**, 277-294.

Salman, M.D. (2003). Surveillance and monitoring systems for animal health programs and disease surveys. Animal disease surveillance and survey systems: methods and applications, pp3-13

Shackleton, R.T., Richardson, D.M., Shackleton, C.M., Bennett, B., Crowley, S.L., Dehnen-Schmutz, K., Estévez, R.A., Fischer, A., Kueffer, C., Kull, C.A. & Marchante, E. (2019). Explaining people's perceptions of invasive alien species: a conceptual framework. *Journal of Environmental Management*, **229**, 10-26

Snyder, M.R., Stepien, C.A., Marshall, N.T., Scheppler, H.B., Black, C.L. & Czajkowski, K.P. (2020). Detecting aquatic invasive species in bait and pond stores with targeted environmental (e) DNA high-throughput sequencing metabarcode assays: Angler, retailer, and manager implications. *Biological Conservation*, **245**, 108430

St-Hilaire S., Beevers N., Way K., Le Deuff R.M., Martin P. & Joiner C. (2005) Reactivation of koi herpesvirus infections in common carp *Cyprinus carpio*. *Diseases of Aquatic Organisms*, **67**, 15–23.

Stärk, K.D., Regula, G., Hernandez, J., Knopf, L., Fuchs, K., Morris, R.S. & Davies, P. (2006). Concepts for risk-based surveillance in the field of veterinary medicine and veterinary public health: review of current approaches. *BMC health services research*, **6**, 20

Stevens, C. H., Croft, D. P., Paull, G. C. & Tyler, C. R. (2017). Stress and welfare in ornamental fishes: what can be learned from aquaculture. *Journal of Fish Biology*, **91**, 409–428

Taylor, N.G.H., Way, K., Jeffery, K.R. & Peeler, E.J. (2010). The role of live fish movements in spreading koi herpesvirus throughout England and Wales. *Journal of Fish Diseases*, **33**, 1005-1007

Taylor, N.G.H., Peeler, E.J., Denham, K.L., Crane, C.N., Thrush, M.A., Dixon, P.F., Stone, D.M., Way, K. & Oidtmann, B.C. (2013). Spring viraemia of carp (SVC) in the UK: the road to freedom. *Preventive veterinary medicine*, **111**, 156-164

Thomsen, P.F. & Willerslev, E. (2015). Environmental DNA–An emerging tool in conservation for monitoring past and present biodiversity. *Biological conservation*, **183**, 4-18

Trujillo-González, A., Becker, J. A. & Hutson, K.S. (2018) Parasite dispersal in the goldfish trade. Advances in Parasitology, **100**, 239–281

Wasserman, R.J., Dick, J.T., Welch, R.J., Dalu, T. & Magellan, K., 2019. Site and species selection for religious release of non-native fauna. *Conservation Biology*, **33**, 969-971

Wheeler, A.C. (1958). Fishes of the London area. *The London Naturalist*, **37**, 80–101

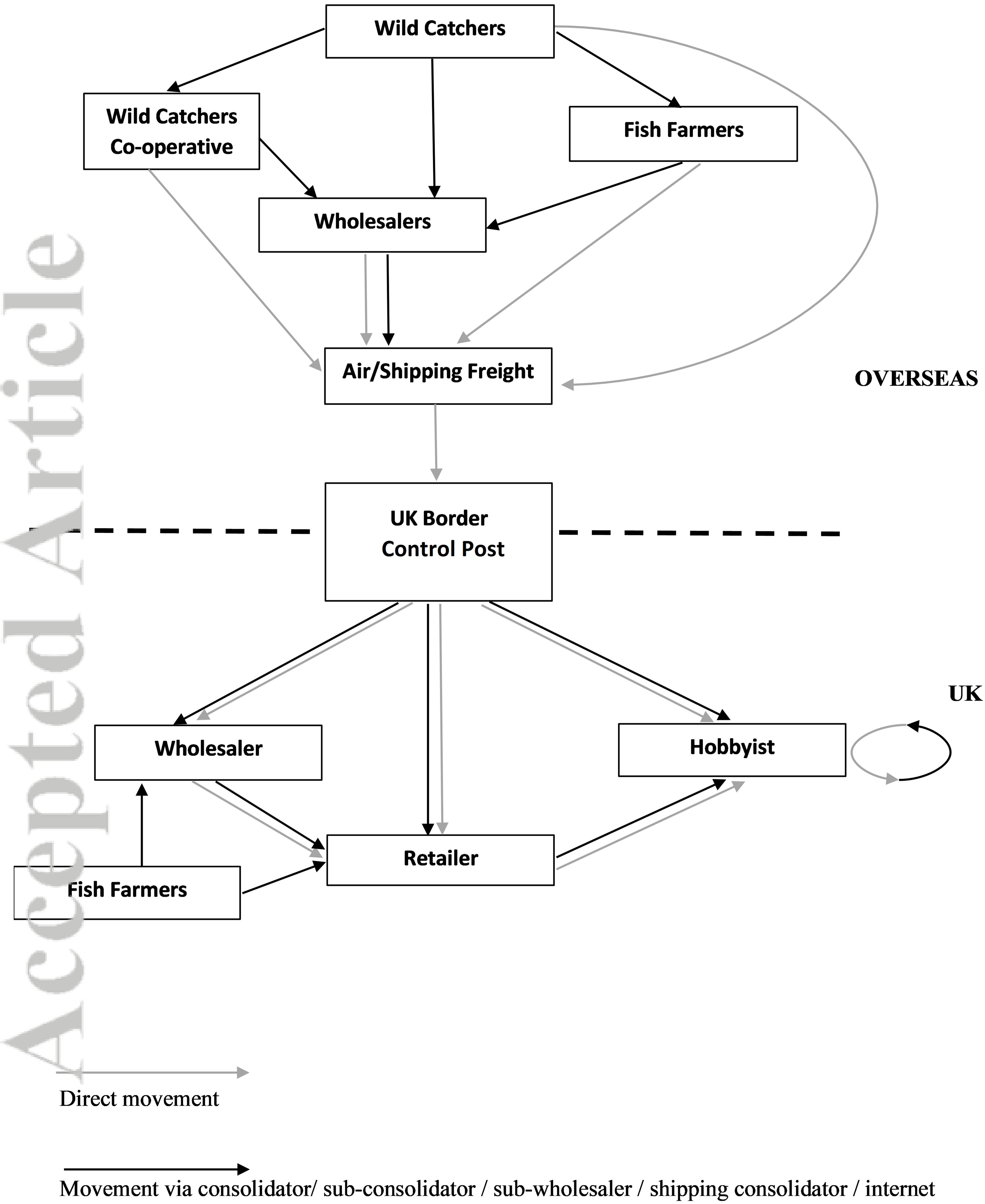
Whittington, R. & Chong, R. (2007) Global trade in ornamental fish from an Australian perspective: the case for revised import risk analysis and management strategies. Preventative Veterinary Medicine, **81**, 92–116

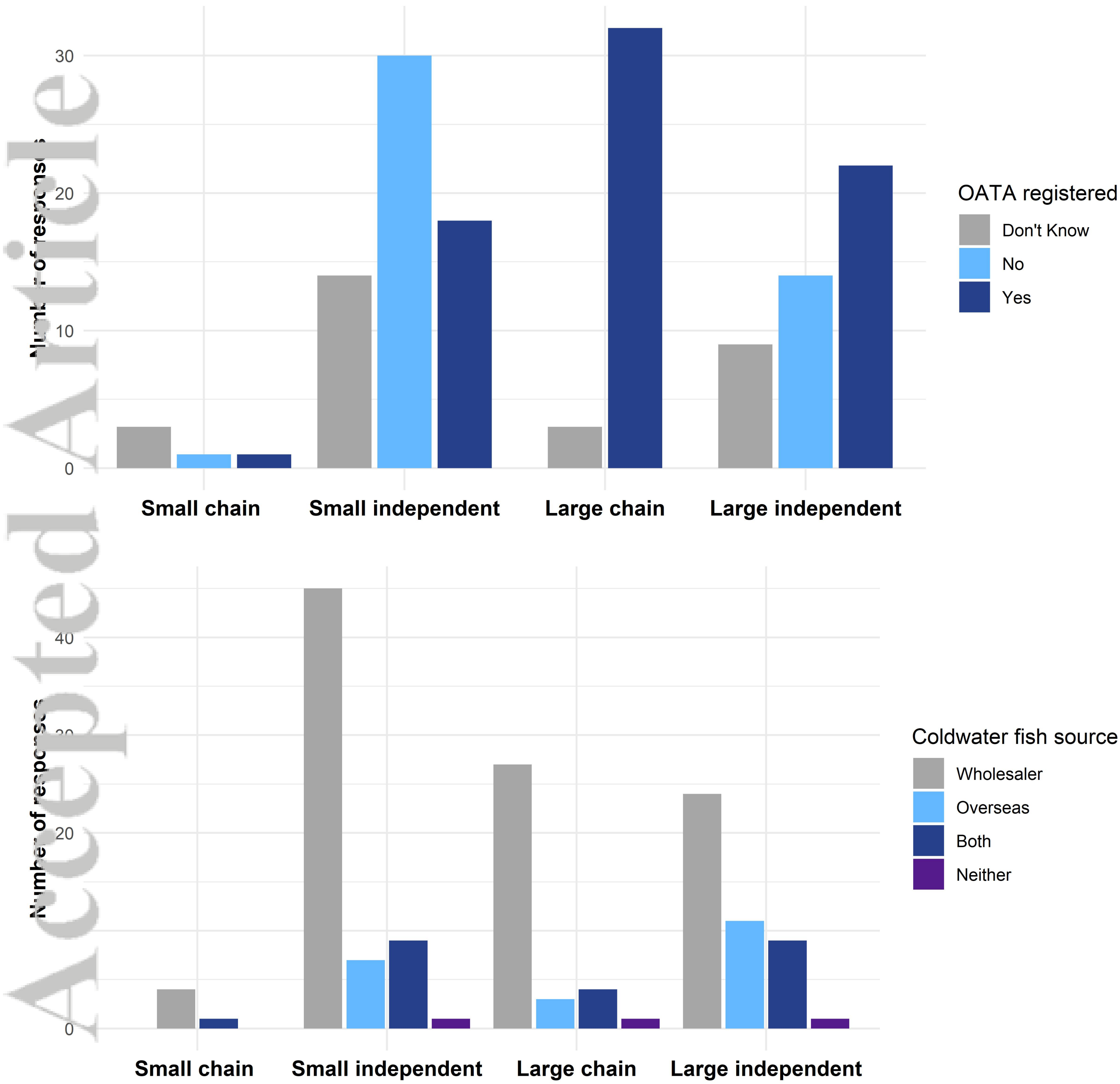
Xu, J.R., Bently, J., Beck, L., Reed, A., Miller-Morgan, T., Heidel, J.R., Kent, M.L., Rockey, D.D. & Jin, L. (2013). Analysis of koi herpesvirus latency in wild common carp and ornamental koi in Oregon, USA. *Journal of virological methods*, **187**, 372-379

Yule, S. (2019). Deadly flesh-eating PIRANHAS found in Yorkshire lake as ducks and fish 'vanish'. *The Mirror*. Available at: https://www.mirror.co.uk/news/uk-news/deadly-flesh-eating-piranhas-found-14385466

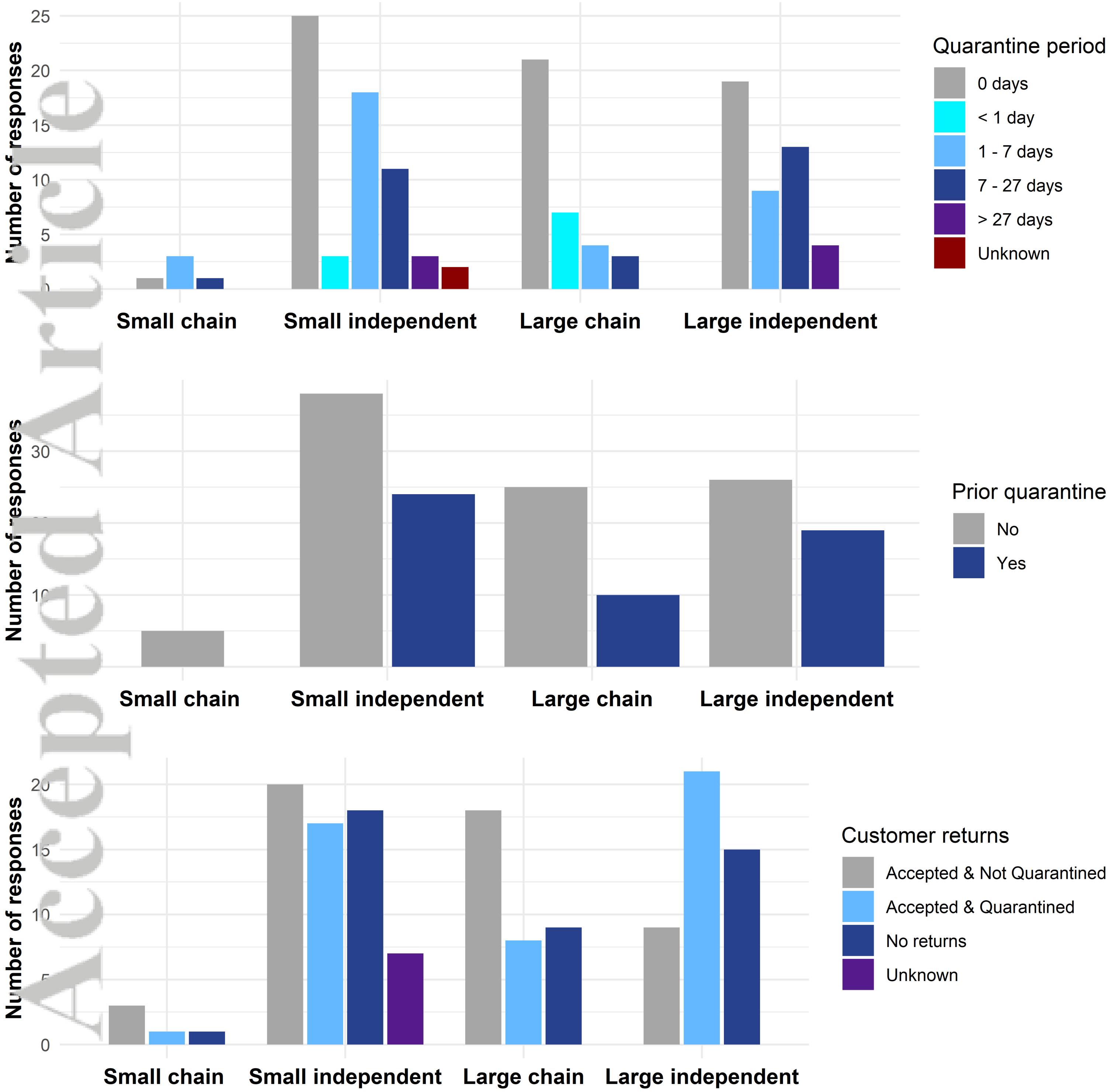
Zeng, D., Cao, Z. & Neill, D.B. (2020) Artificial intelligence–enabled public health surveillance—from local detection to global epidemic monitoring and control. *Artificial Intelligence in Medicine*, **2021**, 437-453

Zheng, S., Wang, Q., Bergmann, S.M., Li, Y., Zeng, W., Wang, Y., Liu, C. & Shi, C. (2017). Investigation of latent infections caused by cyprinid herpesvirus 3 in koi (*Cyprinus carpio*) in southern China. *Journal of Veterinary Diagnostic Investigation*, **29**, 366-369

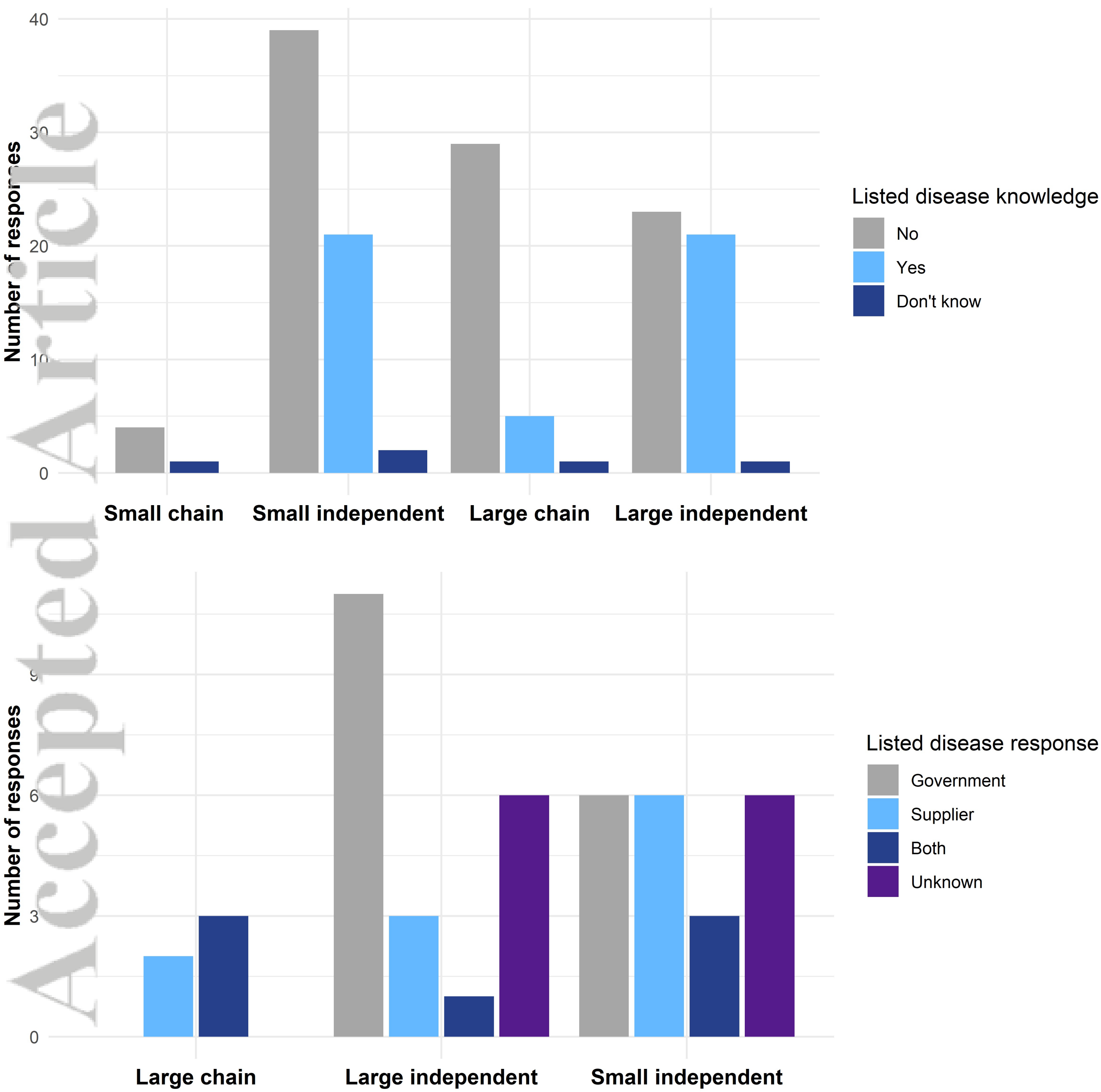

Wild Catchers
Wild Catchers Co-operative
Fish Farmers
Wholesalers
Air/Shipping Freight
OVERSEAS
UK Border Control Post
UK
Wholesaler
Hobbyist
Retailer
Fish Farmers
Direct movement
Movement via consolidator/ sub-consolidator / sub-wholesaler / shipping consolidator / internet

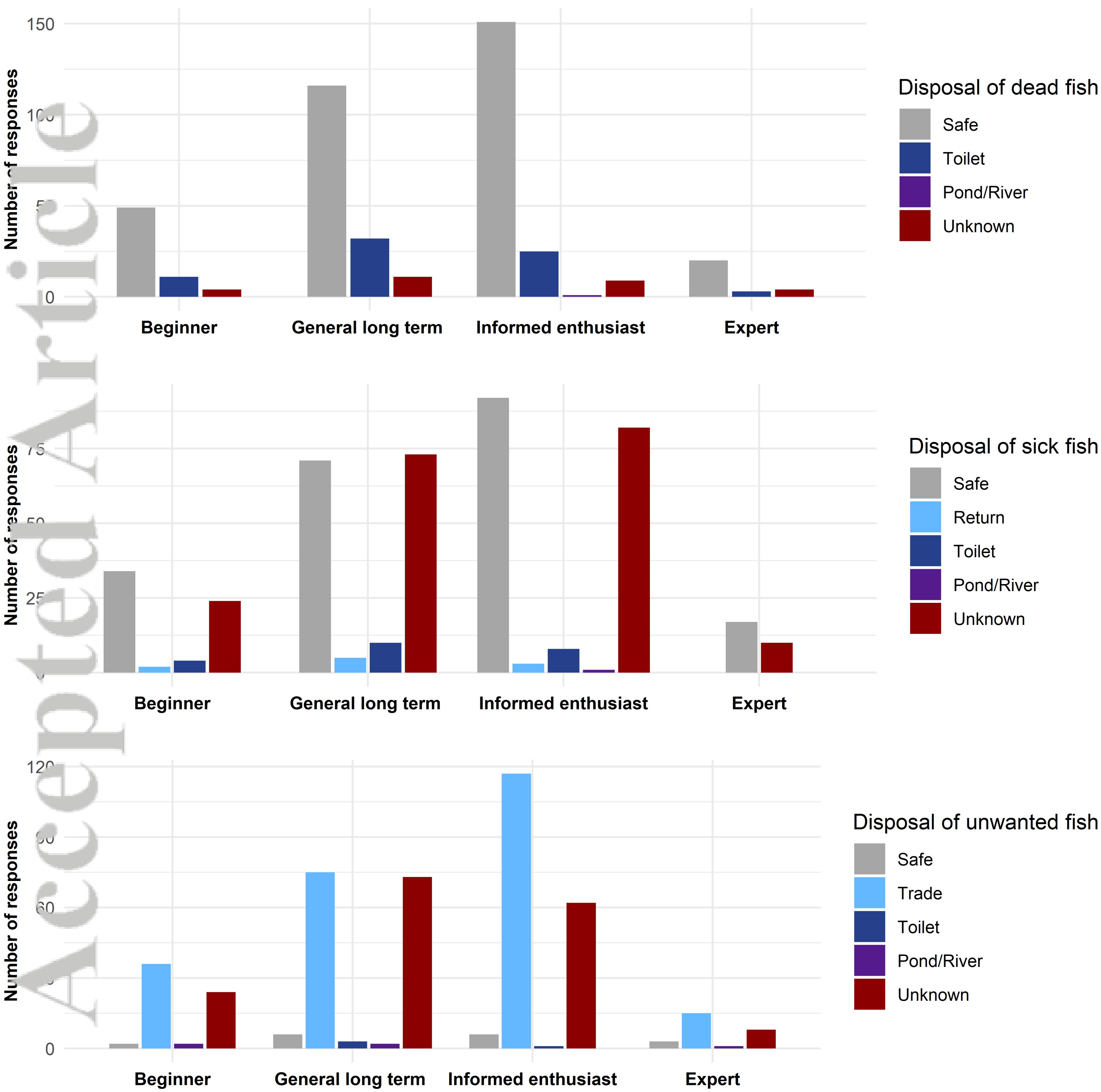


Number of responses
30
20
10
0
Small chain
Small independent
Large chain
Large independent
OATA registered
Don't Know
No
Yes
Number of responses
40
20
0
Small chain
Small independent
Large chain
Large independent
Coldwater fish source
Wholesaler
Overseas
Both
Neither



Number of responses
25
20
15
10
5
Small chain
Small independent
Large chain
Large independent
Quarantine period
0 days
< 1 day
1 - 7 days
7 - 27 days
> 27 days
Unknown
Number of responses
30
Small chain
Small independent
Large chain
Large independent
Prior quarantine
No
Yes
Number of responses
0
Small chain
Small independent
Large chain
Large independent
Customer returns
Accepted & Not Quarantined
Accepted & Quarantined
No returns
Unknown


Number of responses
40
30
20
10
0
Small chain
Small independent
Large chain
Large independent
Listed disease knowledge
No
Yes
Don't know
Number of responses
6
3
0
Large chain
Large independent
Small independent
Listed disease response
Government
Supplier
Both
Unknown


Number of responses
150
0
Beginner
General long term
Informed enthusiast
Expert
Disposal of dead fish
Safe
Toilet
Pond/River
Unknown
Number of responses
Beginner
General long term
Informed enthusiast
Expert
Disposal of sick fish
Safe
Return
Toilet
Pond/River
Unknown
Number of responses
0
Beginner
General long term
Informed enthusiast
Expert
Disposal of unwanted fish
Safe
Trade
Toilet
Pond/River
Unknown

Figures

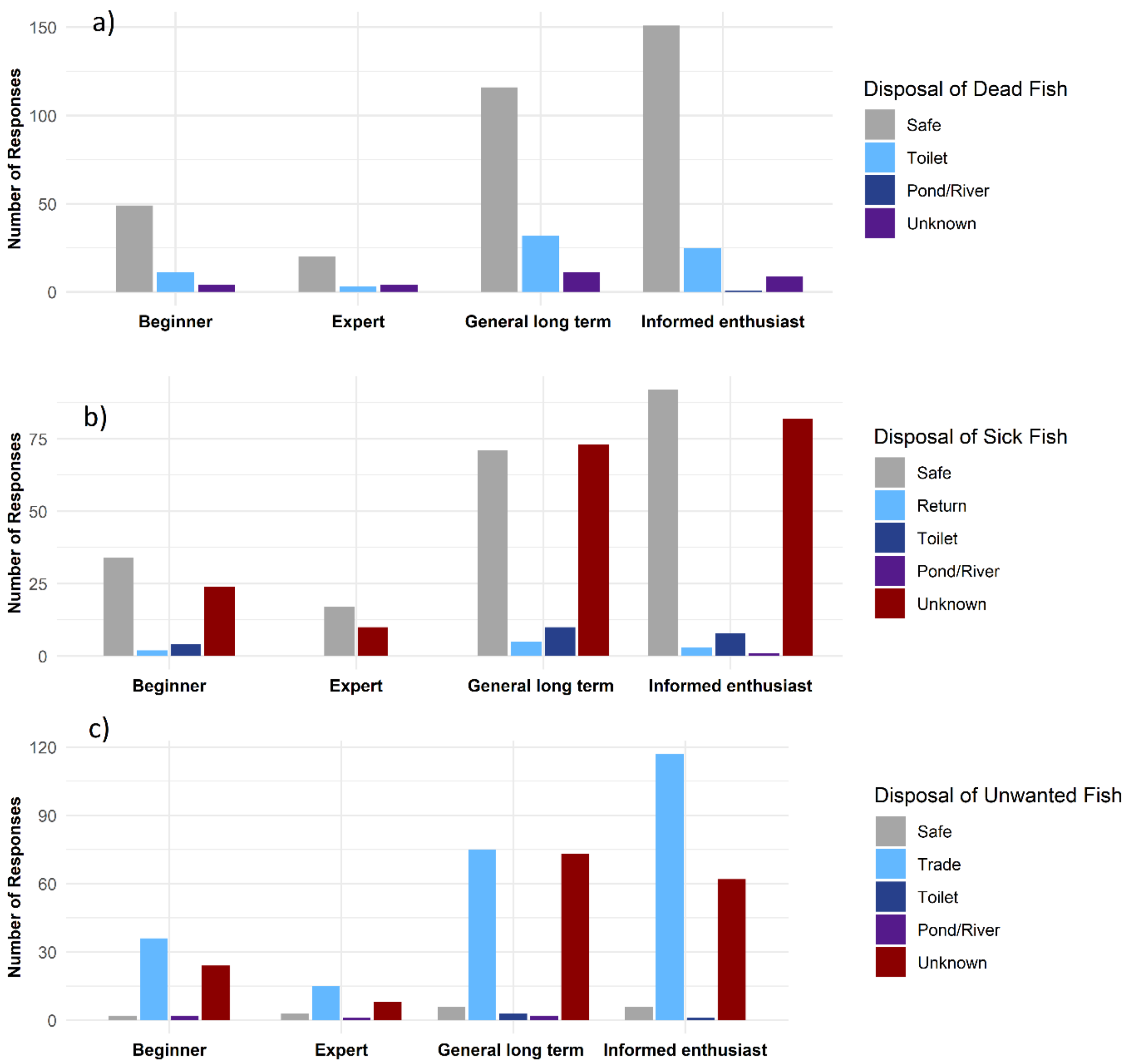
Fig. 1. Representation of the ornamental fish industry supply chain. The pathway of ornamental fish movement will vary between species. Arrows indicate direct contact between actors at physical locations (such as retail shops, exhibitions, airports) and/or indirect contact via postal services using formal or informal online (aquabid, gumtree, and ebay) trading platforms.

Fig. 2. Retailers that were a) OATA registered b) sourced fish from wholesalers and/or overseas, based on the retailer type. Overseas refers to any country that is not the UK and includes both the EU and third countries.

Fig. 3. Quarantine practised observed in retailers a) quarantine period b) perception that quarantine had been carried out prior to arrival at retailer c) quarantine practice if customers returned stock, based on retailer type.

Fig. 4. Retailers reported a) knowledge of OIE listed disease b) reporting response to OIE listed disease, based on retailer type.

Fig. 5. Hobbyist disposal practices of a) dead fish b) sick fish c) unwanted fish, based on hobbyist type.


a)
Number of Responses
0
50
100
150
Beginner
Expert
General long term
Informed enthusiast
Disposal of Dead Fish
Safe
Toilet
Pond/River
Unknown
b)
Number of Responses
0
25
50
75
Beginner
Expert
General long term
Informed enthusiast
Disposal of Sick Fish
Safe
Return
Toilet
Pond/River
Unknown
c)
Number of Responses
0
30
60
90
120
Beginner
Expert
General long term
Informed enthusiast
Disposal of Unwanted Fish
Safe
Trade
Toilet
Pond/River
Unknown

Significance statement: This study improves our understanding of the biosecurity practices and hazard responses implemented at post-border stages of the ornamental fish supply chain. Behaviours were shown to vary considerably within ornamental fish retailers and hobbyists and it was concluded that reliance on these groups to minimise hazard transmission and introduction to the aquatic environment is likely to be ineffective at present. Resources should be allocated towards improving and enforcing robust pre-and at-border control measures.